

Realization of a Four-Electrode Liquid Crystal Device With Full In-Plane Director Rotation

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Abstract—A liquid crystal device with micrometer-scale hexagonal electrodes has been fabricated and characterized. By using weak anchoring at the liquid crystal interfaces, the orientation of the director is completely governed by the applied electric fields. The appropriate voltage waveforms applied to electrodes allow the director in the liquid crystal layer to be rotated in the plane parallel to the substrates over large angles, exceeding 180° . This paper is a technological and experimental verification of an earlier proposed device concept.

Index Terms—Liquid crystals, rotatable wave plate, weak anchoring.

I. INTRODUCTION

THE IN-PLANE switching (IPS) mode of nematic liquid crystals [1] is widely used in commercial flat panel displays. The director in the IPS mode is originally oriented homogeneously along the rubbing direction. The positive and negative electrodes form a pattern of parallel interdigitated strips on the bottom glass substrate at a small angle with the rubbing direction. A voltage applied to the electrodes generates an electric field perpendicular to the electrode strips that rotates the director in the plane parallel to the surface. Switching back in IPS devices is governed by the surface anchoring and the elastic forces of the liquid crystal.

In this paper, a recently fabricated device is presented in which both switching on and switching off are driven by an electric field. In this way, both switching on and switching off are governed by the same mechanism. This implies that both switching times will be of the same order, and the slow relax time in conventional IPS devices can be overcome. In literature, a number of related devices have been demonstrated in which other electrode configurations are used to obtain

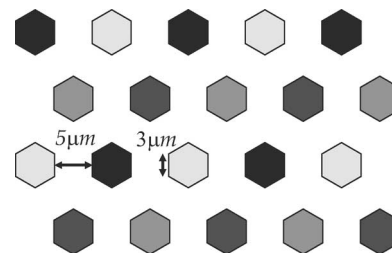


Fig. 1. Distribution of hexagonal electrodes with side $3 \mu\text{m}$ and spacing $5 \mu\text{m}$. The four groups of electrodes are distinguished by their gray scale.

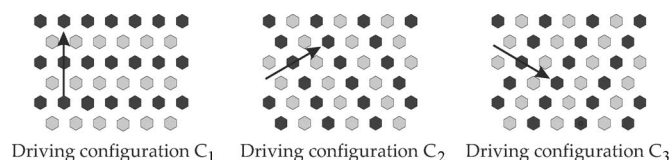


Fig. 2. Three different driving configurations for the hexagonal electrodes. By contacting the four sets of electrodes to two by two, three different field patterns occur. One pattern is transformed into the next by a rotation over 60° . In configuration C_1 , the electrical fields are mainly vertical, and the average director will rotate to this orientation.

similar switching [2]–[7]. In the device presented in this paper, switching is obtained over the whole electrode region with low voltages applied.

The working principle of our device has been reported earlier in [8] by means of dynamic 3-D finite-element simulations [9]. The device is based on hexagonal electrodes arranged in a 2-D array on the bottom glass substrate. By interconnections to underlying metal strips, the hexagonal electrodes are divided in four equivalent groups, as illustrated in Fig. 1. All hexagons belonging to the same group are connected to the same voltage source. Fig. 2 shows that combining the four groups of hexagons in sets of two by two, leads to three different steady-states. In configuration 1, the field pattern associated with the applied voltage is similar to that of an IPS device with horizontal electrodes because the hexagons with equal voltage are arranged in horizontal lines. In this configuration, we can expect that the liquid crystal director will reorient more or less in the vertical direction, which is parallel with the main electric field component. Going from configuration 1 to configuration 2, the director will be rotated roughly over 60° , and consecutive application of the different states enables a 360° in-plane rotation of the director. The steady-state and switching behavior of liquid crystals in these configurations has been numerically demonstrated in [8].

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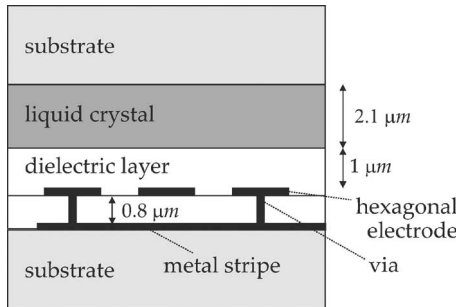


Fig. 3. Cross section of the four-electrode liquid crystal device. The metal strips are connected to the hexagonal electrodes by vias. The dielectric layer below the liquid crystal reduces the field component perpendicular to the substrate.

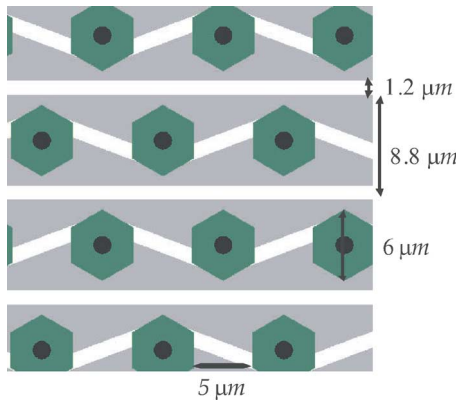


Fig. 4. Top view of the mask design illustrating how the hexagonal electrodes are connected by vias with the metal strips below.

In the following sections, we discuss the design, realization, and switching behavior of a real device. The mask design and fabrication in the clean room has been a joint effort of different research groups in the framework of the European Research Training Network, Synclinic and Anticlinic Mesophases for Photonic Applications (SAMPa) and the Belgian Photon Network.

II. DEVICE DESIGN AND PROCESSING

The cross section of the four-electrode device is illustrated in Fig. 3. The liquid crystal layer is sandwiched between a dielectric layer on the bottom and a glass substrate on the top. The hexagonal electrodes are situated below the dielectric layer, interconnected with the metal strips underneath by vertical conductors or vias through a second dielectric layer. The presence of the dielectric layer between the liquid crystal and the electrodes is important to reduce the electric field components which are perpendicular to the glass substrate [8].

Fig. 4 illustrates how the four groups of hexagonal electrodes are located with respect to the metal strips. The vias are placed in the center of the hexagonal electrodes and make a connection between the hexagonal electrodes and the underlying metal strips. The latter are shaped in such a way that half of the hexagons on a horizontal line are connected to one strip and half of them to the other. In the design phase, it was decided to cover most of the bottom glass substrate with the metal strips, in order to obtain a top surface which is as flat as possible.

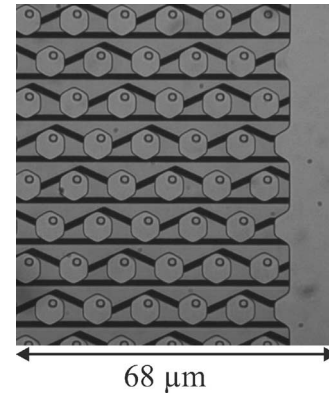


Fig. 5. Microscope image in reflection showing the hexagonal electrodes above the metal strips.

The production process of the substrates consists of the following steps.

- 1) A homogeneous layer of titanium with a thickness of 100 nm is sputtered on the glass substrate. The metal strip pattern is obtained by photolithography and dry etching.
- 2) A homogeneous layer of the polymer BenzoCycloButene 3022–35 (BCB) (Dow Chemical [10]) with a thickness of approximately $0.8 \mu\text{m}$ is deposited by spin coating on the substrate. The location of the vias is defined on the dielectric layer by photolithography, and the holes are made by dry etching.
- 3) On top of this, a homogeneous layer of titanium with a thickness of 100 nm is sputtered. The holes in the previously deposited dielectric layer are filled with the metal during the sputtering process. This ensures the required interconnection between the top and bottom metal layer. In a photolithographic step, the hexagonal electrodes are defined, and the excess titanium is removed by dry etching.
- 4) A second layer of BCB with a thickness of $1 \mu\text{m}$ is deposited on the substrate by spin coating.

A microscope image of one of the hexagonal pixels is shown in Fig. 5. The mask for defining the hexagonal electrodes was slightly misaligned during the manufacturing process. This explains the excentric location of the hexagonal electrodes with respect to the vias and the metal strips in Fig. 5. This slight misalignment has no detrimental influence on the device working.

For the dielectric layers, it was decided to work with the polymer BCB because of its excellent planarizing properties, as was shown in [11]. This paper states that a BCB coating thickness of twice the largest step height reduces the step height at the top surface at least by a factor 5. Since the 100-nm step size due to the titanium electrodes is much smaller than the thickness of the BCB layers (respectively, 800 and 1000 nm), the remaining nonuniformity is negligible. The spin coating process itself does induce any important nonuniformity. From previous tests, it was estimated that the nonuniformity was below 20 nm. BCB has a relative dielectric constant $\epsilon \sim 2.5$ and a refractive index $n = 1.561$ (Dow Chemical Company). The dielectric constant is lower than the value that was used

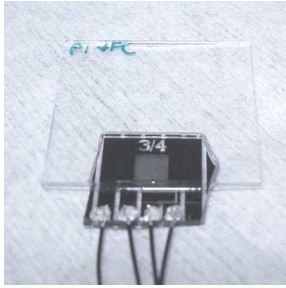


Fig. 6. Photograph of a finished four-electrode liquid crystal device with four soldered wires. The bottom substrate is $1/2 \times 1/2$ in, and the top substrate is a simple glass plate of 1 in².

for the simulations [8], so a thickness of only $1 \mu\text{m}$ was used (instead of the original $1.3 \mu\text{m}$).

The finished bottom substrate (12×12 mm in size) and the bare top glass substrate (25×25 mm in size) are covered with a surfactant FC4430 by dip coating to obtain planar alignment with weak anchoring for the liquid crystal director. The Fluorad FC-4430 (from 3M) is a nonionic polymeric fluorochemical surfactant providing low surface tension. The azimuthal anchoring strength is weak. Its value has been estimated from other experiments as $W_a = 3.6 \times 10^{-7} \text{ J/m}^2$ [12]. This is comparable with the value obtained by others [3]. For E7, this weak anchoring energy is equivalent to an extrapolation length [13] of $25 \mu\text{m}$. For such a weak alignment, the angle between the director near the interface and the preferential direction can be considerable.

Finally, the two substrates are glued together using Norland Optical Adhesive NOA-68. To ensure a liquid crystal layer with a constant thickness of $2.1 \mu\text{m}$, spherical glass spacers with a diameter of $2.1 \mu\text{m}$ are added to the glue. The cell was filled by capillary forces with the liquid crystal mixture E7 [14] while heated above the nematic/isotropic transition temperature and then slowly cooled. Fig. 6 shows a completed cell after the four contact wires have been soldered to the bottom glass substrate.

III. DEVICE OPERATION

After fabrication of the cell, the operation under voltage driving was investigated. The switching behavior was observed with a polarizing microscope. As the metal electrodes cover most of the bottom substrate, the microscope observations are carried out in reflection with crossed polarizers in the incident and reflected light path. Fig. 7 shows the reflection microscope image for crossed polarizers when no voltage is applied. The weak anchoring related to the fluorosurfactant FC-4430 and the absence of a preferential direction (no rubbing) lead to a Schlieren texture [15] with large lateral dimensions [16]. The director orientation in the different regions was found by rotating the sample and by observing the variations under influence of small electric fields. The director orientation is visualized in Fig. 7 by small white lines.

Fig. 8 shows how the Schlieren texture is modified when an increasing voltage is applied with configuration C_1 . A square wave voltage with a frequency of 120 Hz is used to avoid a voltage drop related to the motion of ions. In this case, hexagons on the same line experience the same voltage, and

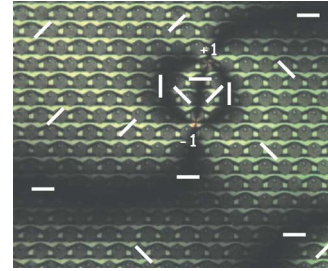


Fig. 7. Reflection microscope image of the four-electrode liquid crystal device with 0 V applied. The white stripe indicates the director orientation in the different regions of the Schlieren texture. Two defects are indicated.

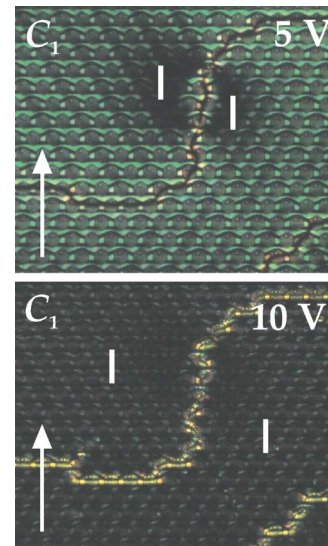


Fig. 8. Reflection microscope image of the four-electrode liquid crystal device with different voltages applied in configuration C_1 . For 5 V applied, (top) the region with vertical has grown. For 10 V, (bottom) the director is vertical, except in an inversion wall, appearing as a bright line.

the fields are mainly in the vertical direction. When 5 V is applied, the regions with vertical director grow, and the regions with horizontal director shrink. At 10 V, most of the area has a homogeneous director orientation, which is perpendicular to the metal strips. There is a surface inversion wall visible in the picture, in which the director makes an in-plane rotation of 180° .

In Fig. 9, the polarization reflection image is shown for the driving configuration C_2 when 10 V is applied. The reflection is roughly homogeneous, but the image is not dark because the mean director makes an angle of 60° with the polarizer. The orientation of the director can be verified by rotating the substrate over 60° in such a way that the director coincides with one of the polarizers. The result is indeed a dark image. For the driving configuration C_3 , a similar result is obtained, and the dark state is reached after a rotation of -60° . The dark state here is not as good as the one in Fig. 8 for the driving configuration C_1 . This can be explained by a residual influence of the metal strips below the hexagonal electrode patterns. The electric field related to the metal strips is not completely shielded by the hexagons, and this promotes the orientation of the director perpendicular to the metal strips, as in configuration C_1 .

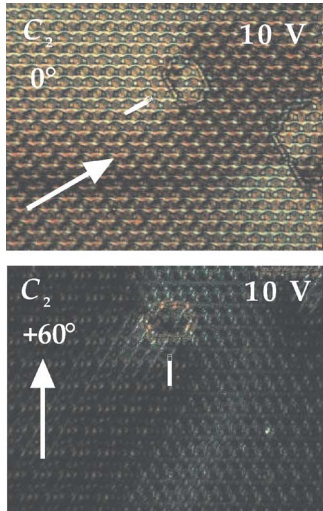


Fig. 9. Reflection microscope image of the four-electrode liquid crystal device with 10 V in configuration C_2 . The director makes an angle of about 60° with the polarizer, (top) yielding a bright image. Rotating the device over 60° (bottom) yields a dark state with the director perpendicular to one of the polarizers.

IV. DISCUSSION

The experiments described previously with the four-electrode liquid crystal device are largely in agreement with the predictions of the simulation work [8].

The switching time of the device as currently implemented is in the order of 300 ms, which is the time necessary for all regions in the device to achieve the steady state. This is much larger than the predicted by the simulations in [8]. The switching to one of the defined states is slowed down to some extent by the long-range collaborative director rotations. Instead of a homogeneous director rotation after applying a different driving configuration, homogeneous regions grow initiated at the inversion walls. This process results in a large switching time. In order to speed up the reorientation process, larger voltages can be applied. Since all states are voltage controlled, the switching times to different states are all equal. This is different from the usual liquid crystal configurations where one state is reached by applying a voltage and the other state by switching off the voltage, whereby the reorientation occurs due to interface anchoring.

In the experiments carried out here, the initial random Schlieren pattern is a result of cooling down from the isotropic phase. It would be preferable to start from a homogeneous director, in order to obtain homogeneous and faster switching without inversion walls. A further reduction of the surface anchoring strength will allow domains growing during the cool down process to reorient the director and disclination points to annihilate each other when merging together. A better way, however, is to prealign the liquid crystal director during the isotropic to nematic phase transition. This can be done first of all by applying a voltage to the electrodes, but the generated field is only on average unidirectional then. The best way would be by externally applying an in-plane constant magnetic field during the cool down process. A different approach would be to use weakly anchored multistable surfaces, allowing three

stable orientations of the liquid crystal surface director [4]. Also, it is possible to apply parallel rubbing to the interfaces. In this way, the zero field state could be homogeneous and the bright states field-induced, while it would still be possible to actively change the director orientation in both directions with the smart electrodes. For display applications, a slight change in the layout should make it possible to switch the average director over 45° instead of the 60° now, so that a maximal amplitude modulation can be achieved.

Applications of the new device are mainly situated in the field of electrically controllable retarders. The four-electrode liquid crystal device can be used as wave plate with variable optical axis, which is electrically controllable. By further improving weak surface anchoring, the director configuration could be maintained by applying a small voltage. Switching off the voltage now leads to the same Schlieren pattern that was observed at the beginning. If the dimension of the electrode structure can be further reduced, the principle of the hexagonal electrode switching can be considered as a commanding interface that determines the anchoring in the vicinity of the interface. In combination with a rubbed alignment layer as counter substrate, this allows to switch from a homogeneous layer to two twisted configurations with opposite rotation. For further discussion of possible applications, we would like to refer to [8].

We would like to stress that the purpose of the current device was solely to prove the working principle. When proceeding to a next demonstrator device, the decision should be made whether this device will work in a reflective or a transmissive configuration. For reflective configurations, it is desirable that the electrode patterns fill the surface as much as possible. For transmissive configurations, the electrode surface should be as small as possible or even transparent using indium tin oxide. In the current device, the bottom electrode layer covers almost entirely the surface. The fill factor can be drastically decreased by taking only small strip electrodes in the interconnection layer. In this way, the aperture ratio is mainly determined by the second electrode layer, and in the current design, this would result in an aperture ratio of 84.3%.

In a next implementation of this technology, the optical properties such as the transmission, contrast ratio, and uniformity are important issues, but investigating these parameters experimentally is not trivial. Optical simulations using coupled-wave methods have been carried out, and experiments to measure these parameters are planned. The results of this paper will be the subject of a future publication.

V. CONCLUSION

A four-electrode liquid crystal device based on hexagonal electrodes of micrometer-scale dimensions has been realized. The hexagonal electrodes are addressed by metal strips through vias, and weak anchoring is used to allow the rotation of the director in the vicinity of the electrodes. The device operates like a rotatable wave plate. If the appropriate voltage waveforms are applied, the director in the liquid crystal switches between three relatively homogeneous states.

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REFERENCES

- [1] E. Lueder, *Liquid Crystal Displays: Addressing Schemes and Electro-Optical Effects*. Chichester, U.K.: Wiley, 2001.
- [2] A. J. Davidson, S. J. Elston, and E. P. Raynes, "Optical properties of the Cartwheel cell," *J. Phys. D, Appl. Phys.*, vol. 38, no. 3, pp. 376–384, Feb. 2005.
- [3] R. Yamaguchi, T. Yamanaka, and S. Sato, "Liquid-crystal optical rotator using weak azimuthal anchoring surface," *Jpn. J. Appl. Phys.*, vol. 40, no. 11, pp. 6522–6525, Nov. 2001.
- [4] J. H. Kim, M. Yoneya, and H. Yokoyama, "Tri-stable nematic liquid-crystal device using AFM-fabricated micro-patterned surface alignment," *Nature*, vol. 420, no. 6912, pp. 159–162, Nov. 2002.
- [5] I. Dierking, L. Komitov, and S. T. Lagerwall, "On in-plane smectic layer reorientation in ferroelectric liquid crystal cells," *Jpn. J. Appl. Phys.*, vol. 37, no. 1A/B, pp. L57–L60, Jan. 1998.
- [6] M. Ozaki, H. Moritake, K. Nakayama, and K. Yoshino, "Smectic layer rotation in antiferroelectric liquid-crystal," *Jpn. J. Appl. Phys.*, vol. 33, no. 11B, pp. L1620–L1623, Nov. 1994.
- [7] K. Nakayama, H. Moritake, M. Ozaki, and K. Yoshino, "Smectic layer rotation in ferroelectric liquid crystals," *Jpn. J. Appl. Phys.*, vol. 34, no. 12A, pp. L1599–L1602, Dec. 1995.
- [8] C. Desimpel, J. Beeckman, H. Desmet, K. Neyts, R. James, and F. A. Fernández, "A four-electrode liquid crystal device for 2π in-plane director rotation," *J. Phys. D, Appl. Phys.*, vol. 38, no. 21, pp. 3976–3984, Nov. 2005.
- [9] F. A. Fernández, S. E. Day, P. Trwoga, H. Deng, and R. James, "Three dimensional modeling of liquid crystal display cells using finite elements," *Mol. Cryst. Liq. Cryst.*, vol. 375, no. 1, pp. 291–299, 2002.
- [10] *Cyclothe Advanced Electronics Resins—Dow Chemical*. [Online]. Available: <http://www.dow.com/cyclotene>
- [11] M. H. Schuck, D. J. McKnight, and K. M. Johnson, "Spin-cast planarization of liquid-crystal-on-silicon microdisplays," *Opt. Lett.*, vol. 22, no. 19, pp. 1512–1514, Oct. 1997.
- [12] C. Desimpel, F. Beunis, H. Desmet, and K. Neyts, "Experiments on azimuthal degenerated anchoring surfaces," in *Proc. SPIE, 16th Conf. Liquid Crystals—Chemistry, Physics and Applications*, Stare Jablonki, Poland, 2006, p. A28.
- [13] M. Yonega, K. Iwasaki, Y. Tomioka, and K. Kondo, "Cell gap margin enlargement of in-plane switching mode liquid crystal displays using weak-anchoring effects," *Appl. Phys. Lett.*, vol. 74, no. 6, pp. 803–805, Feb. 1999.
- [14] P. Yeh and C. Gu, *Optics of Liquid Crystal Displays*. New York: Wiley-Interscience, 1999.
- [15] I. Dierking, *Textures of Liquid Crystals*. Hoboken, NJ: Wiley, 2003.
- [16] G. P. Bryan-Brown, E. L. Wood, and I. C. Sage, "Weak surface anchoring of liquid crystals," *Nature*, vol. 399, no. 6734, pp. 338–340, May 1999.



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